Evaluation of the Impact of Standing Support on Ground Behavior in Longwall Tailgates

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ABSTRACT

Longwall mines typically use some form of standing support for secondary roof support in longwall tailgate entries. Although there have been several new support products developed for this application, there remains no universal design criteria to optimize the application of these support technologies. The requirement for optimization and proper support selection is to understand the degree of control that the support has on the ground behavior. The ground reaction curve and numerical modeling was used to evaluate the impact of standing support on ground behavior. LaModel was used to evaluate the impact of standing support on main roof and floor behavior and pillar yielding. The conclusion drawn from this study was that standing supports do not have sufficient capacity to control main roof or floor loading or prevent the resulting convergence of the tailgate entry. However, it is imperative that this "uncontrollable convergence" be considered in the support design to prevent premature failure of the support. A FLAC model was used to evaluate the near-seam roof and floor behavior in conjunction with the global vertical and horizontal stresses. The model suggests that standing roof supports can have some impact on the ground behavior as the elastic response of the rock is exceeded and rock structure deteriorates from the stress concentrations that develop around the tailgate opening. During this phase, the capacity and stiffness of the standing support can be critical to the stability of the opening, as eventually the rock mass will be transformed into a partially detached structure whose weight must be supported by the standing support. This work is part of a ground control program of research at the National Institute for Occupational Safety and Health (NIOSH) aimed at improving mine safety by reducing roof fall injuries and fatalities.

INTRODUCTION

During the past decade, there has been a substantial increase in the development of new and innovative concepts for standing roof support. Currently, there are over 50 different standing support systems available, each with a distinct loading characteristic. They vary considerably in capacity, stiffness, and yield characteristics. So, on what basis is one support chosen over another? Which support will provide the most effective roof support in a particular mining condition? These questions define critical issues in roof support design.

Statement of the Problem

The performance characteristics of these standing roof support systems have been well defined through rigorous full-scale testing and documented in the NIOSH Support Technology Optimization Program (STOP) (Barczak, 2000). A great deal of knowledge has been gained in recent years about the ground behavior associated with underground coal mining through numerous field studies and, more recently, improvements in numerical modeling capabilities. However, there is very little known about the interaction between the support and the ground. How much control do the standing supports have on roof behavior? Do they influence the stress changes and ground movement around the opening? Is it simply a matter of having sufficient capacity to ensure stable roof conditions, or is there a limit to the control that a support has on the roof behavior, and if so, what degree of control does it have? Until this understanding is developed, proper support design cannot be accomplished, and premature failures of supports or excessively conservative applications of support will continue.

Technical Approach

Physical studies of the interaction of support and ground are difficult to accomplish. Since the ultimate goal is to determine the impact of the support on ground control, the study must examine the complete mine roof and floor response in relation to different support characteristics. Because in-mine measurements of stress and deformation of the ground are difficult to obtain, it is impractical to make these measurements, except at a few discrete points, which provides uncertainty in evaluating the complete ground behavior. Furthermore, the load conditions in the mine vary constantly, making it virtually impossible to evaluate the impact of subtle changes in loading which are likely to be present in every study, even if the support parameters are well controlled. These barriers provide justification to approach the evaluation of support and strata interaction through numerical modeling means, which is the approach used in this study.

Two numerical modeling software systems were utilized: (1) LaModel and (2) FLAC. LaModel is a displacement-discontinuity numerical program that can determine the convergence over a coal seam with the overburden responding as a laminated elastic rock mass and with yielding elements in the coal seam (Heasley and Salamon, 1996). These capabilities make it suitable to evaluate the interaction of standing support with the main roof and floor subsidence and pillar yielding. However, the model cannot evaluate any inelastic behavior or failure of the roof or floor that is common in the near-seam ground behavior. FLAC was used for this purpose, instead, and is a finite-difference software program that was used to investigate the effect of rock failure and post peak behavior on rock-support interaction (HCItasca, 2003). The FLAC model is therefore able to provide a more detailed analysis of the near-seam rock response associated with particular support applications.

Scope of Study

The focus of this effort is a study of standing support interaction with the surrounding rock in a longwall tailgate. The LaModel studies evaluated loading conditions both outby and inby the longwall face. FLAC modeling was limited to an evaluation of support and strata interaction for abutment loading conditions outby the longwall face. This simplifies the evaluation by allowing a two-dimensional assessment of the loading conditions, a requirement to keep the modeling size manageable for the detailed assessment of the near-seam rock mass. A geological condition representative of the Pittsburgh seam in a western Pennsylvania mine was also used as the basis for this study.

CONCEPTUAL MODEL OF ROCK MASS BEHAVIOR AND SUPPORT INTERACTION

The interaction between standing supports and the surrounding rock mass can best be explained in terms of a conceptual ground reaction curve shown in Figure 1 (Brady and Brown, 1985). The curve represents roof-to-floor convergence as a function of the internal support pressure plotted to a logarithmic scale in an entry that is subject to abutment loading. The curve shows that if zero convergence is desired, the support pressure should equal the initial stresses in the rock, point A on the curve. However, if the internal support pressure is reduced, convergence will occur. Initially, the convergence occurs in response to elastic relaxation of the rock mass, section A–B on the curve. As the support pressure is further reduced, rock failure and pillar yield can occur which will increase the rate of convergence, section B-C on the curve. When the support pressure is reduced even further, the failed rock mass will loosen and the dead weight of the loosened material will rest on the support. This will result in an increase in loading of the supports, section C-D on the curve. The curve is known as the "required support line" and has been proposed as a methodology for understanding roof support requirements, because it represents the support pressure required to achieve equilibrium in the entry (Mucho, et al., 1999).

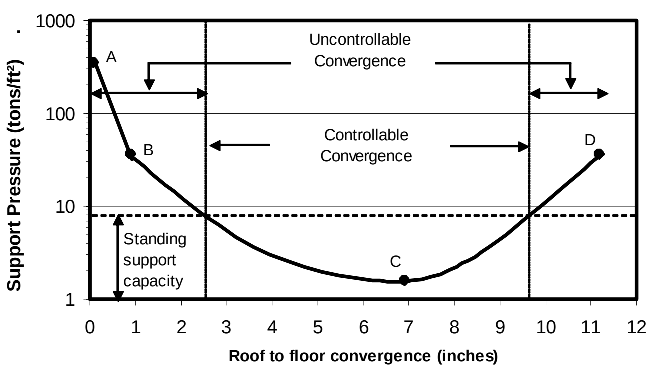

Figure 1. Ground Reaction Curve approximation for outby loading conditions in a longwall tailgate.

Figure 1 also shows the typical support resistance provided by standing supports. It can be seen that the support resistance is very small relative to the initial part of the ground reaction curve. The convergence during this part of the curve is called "uncontrollable convergence" because the required support line is overwhelmingly greater than the available support capacity. However, after sufficient convergence has occurred, the support capacity exceeds the required support line and equilibrium will be achieved in the entry. This is referred to as "controllable convergence". The convergence can become uncontrollable if the supports yield excessively and loosening of the rock mass is allowed to occur.

The ground reaction curve shows that standing supports must survive the initial uncontrollable convergence and should retain sufficient capacity to exceed the required support line. Increasing the support capacity beyond that of the typical support would only have a minor effect on the uncontrollable convergence, owing to the steepness of the required support line.

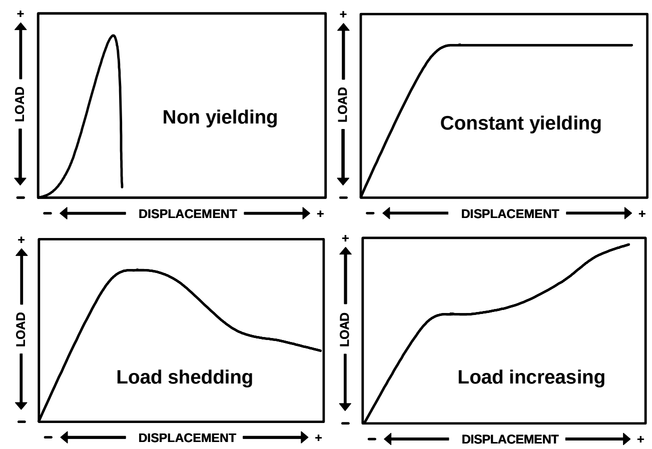

Figure 2. Four basic types of loading characteristics for standing roof support systems.

STANDING SUPPORT SYSTEMS INCLUDED IN THIS STUDY

As indicated in the introduction, there are a wide variety of standing support systems currently available for longwall tailgate application. Although their performance characteristics vary, they can be classified into four basic types as illustrated in figure 2: (1) non-yielding, (2) constant yielding, (3) load-increasing or strain-hardening yielding behavior, (4) load-shedding or strain-softening yielding behavior. Supports chosen for this particular study that are representative of each of these types of supports were the concrete donut crib (non-yielding), conventional 4-point wood crib (load increasing), pumpable roof support (load shedding), and the Can[1] support (constant yielding). A comparison of their load-displacement characteristics is shown in figure 3. The concrete donut crib has the highest capacity and stiffness, but quickly looses its capacity after reaching its peak load, making it a non-yielding support. The pumpable roof support is a grout-filled support that is formed in place in the mine entry by pumping a specialized grout into a fabric bag that is hung from the mine roof. The pumpable roof support has the second highest capacity and stiffness of the four supports considered in this analysis and is classified as a load-

[1]Mention of company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

shedding support. The Can support comes in several sizes. A 24-in diameter Can was chosen for this study. It is stiffer than a wood crib with a higher yield capacity and is able to sustain its peak loading through a large displacement. The Can support is considered a constant yielding support. The wood crib is the softest support system, but increases its load carrying capacity as it yields. The properties of each of these supports were determined from full-scale testing in the NIOSH Mine Roof Simulator.

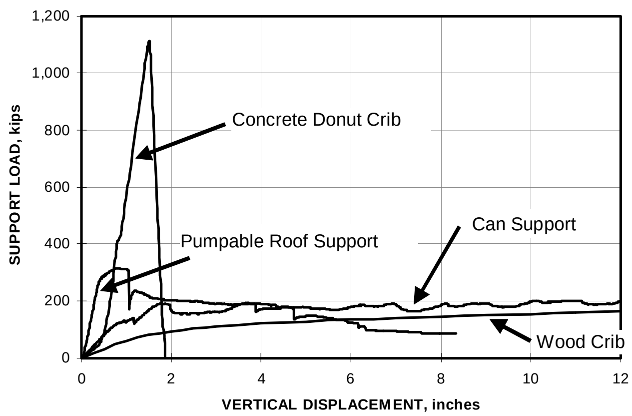

Figure 3. Actual loading characteristics of standing support systems chosen for study based on full-scale testing in NIOSH Mine Roof Simulator.

NUMERICAL MODELING STUDIES OF SUPPORT AND STRATA INTERACTION

LaModel and FLAC models were utilized to evaluate the impact of roof support on ground behavior. As stated in the scope of work, LaModel was utilized to evaluate the response of the main roof and floor and pillar yielding for the full tailgate condition both outby and inby the longwall face, while FLAC focused on the response of the near-seam rock mass for outby loading conditions only. The experimental design and results of these studies are provided.

Evaluation of the Outby and Inby Tailgate Conditions with LaModel

Input into the model includes the model geometry, the overburden, coal and support properties, and the mining depth. The model elements were 4 ft by 4 ft. A description of these input parameters and a parametric support study are described.

Model Layout and Loading Conditions. Figure 4 shows the three-entry gateroad system with two adjacent panels that was evaluated in this analysis. Each longwall panel was approximately 800 ft wide. The abutment pillars were 88 ft wide and 180 ft long and the entries were 20 ft wide, providing a gateroad system with a width of 236 ft. A 1,000-ft section of the gateroad, 500 ft inby and 500 ft outby the longwall face, was evaluated. This area represents the full range of tailgate conditions that the standing support may be subjected to, including the front abutment pressures outby the face and the main roof-to-floor subsidence caused by the adjacent gob inby the face. The seam thickness was 6 ft. As shown, the tailgate entry under consideration is adjacent to panel 2. In figure 4, the first panel has been mined and the second panel has been partially mined. This represents the situation that was used to evaluate the standing support performance. Overburden depths of 600 and 900 ft were modeled with the initial stress condition based on a stress factor of 1.1 psi per ft of overburden.

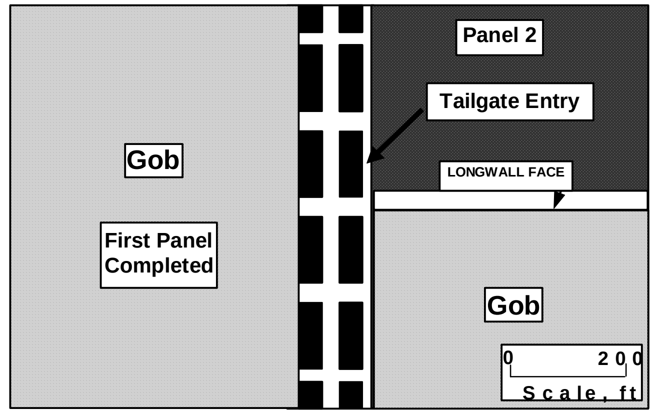

Figure 4. Three-entry gateroad system with two adjacent panels utilized in LaModel study.

Coal, Overburden, and Support Properties. Both elastic and elastic-plastic elements were used for the coal material with an elastic modulus of 300,000 psi and a Poisson's ratio of 0.33. The elastic elements were used for coal that is a sufficient distance from the openings and do not yield and were considered to have infinite strength. The elastic-plastic behavior was applied for those elements closer to the opening that could yield. The coal strength for the elastic-plastic elements was developed from the Bienawski strength formula, where the base strength for the coal was 900 psi (Mark and Chase, 1999). The coal strength then increases with distance from the opening because of confinement. After yield, the deformation modulus of the elastic-plastic elements was zero. For the overburden, an elastic modulus of 3 million psi and a lamination thickness of 50 ft were used in the analysis (Heasley and Chekan, 1999). Strain-hardening elements were used for the gob material. The initial elastic modulus was 100 psi with a Poisson's ratio of 0.25. At the 900-ft depth, the peak gob stress was 495 psi with a final elastic modulus of 22,500 psi, and at the 600 ft depth, the peak gob stress is 330 psi with a final elastic modulus of 33,700 psi.

The support properties are defined in terms of strain-softening and elastic-plastic element behavior in the model. Elastic-plastic elements are used to approximate the behavior of the Can support and wood cribs, while the strain-softening elements are used to approximate the behavior of the pumpable roof support and concrete donut cribs.

Parametric Study. In this study, four parameters were varied that include the support type, the amount of support, the pillar design, and the overburden depth. The four support types used in the models were discussed previously. The performance of each type of support was evaluated through changes in the other three parameters. The supports were placed along two rows down the tailgate with each row centered 6 ft from the middle of the entry. The support density was varied by changing the support spacing within a row. Two support densities were examined, a 4-ft and an 8-ft center-to-center spacing. The supports were installed after the first panel had been mined but prior to mining of the second panel.

Two pillar designs were evaluated in the study. For both designs, the gateroad system width remained the same. One system had two stiff, abutment pillars that were each 88 ft in width. This

Table 1. Roof-to-floor convergence at selected locations for the case with a depth of 900 ft and 88-ft pillars for both 4-ft and 8-ft support spacing

	Roof-to-Floor Convergence, in				
Location, ft[1]	No support	Concrete donut cribs	Wood cribs	Pumpable roof supports	Can supports
			8-ft support spacing		
18	0.777	0.764	0.775	0.770	0.774
0	1.186	1.181	1.183	1.178	1.181
-34	2.113	2.107	2.109	2.106	2.106
-200	5.656	5.657	5.649	5.650	5.645
			4-ft support spacing		
18	0.777	0.754	0.773	0.764	0.770
0	1.186	1.158	1.180	1.171	1.176
-34	2.113	2.102	2.105	2.100	2.100
-200	5.656	5.661	5.641	5.644	5.587

[1]Negative numbers refer to locations inby the longwall face.

was the base model where the affects of support density and the overburden depth were evaluated. The other system had an abutment-yield pillar design with an abutment pillar width of 148 ft and a yield pillar located adjacent to the tailgate entry with a width of 28 ft. Two overburden depths, 600 ft and 900 ft were modeled. The base depth was 900 ft.

Roof-to-Floor Convergence Analysis. To evaluate the impact of the standing support on roof and floor behavior with LaModel, the roof-to-floor convergence in the tailgate was analyzed. Figure 5 shows the roof-to-floor convergence of the tailgate entry with no standing support for a distance of 500 ft inby and 200 ft outby the longwall face for the two pillar geometries and the two different mining depths. The largest convergence occurred with the abutment-yield pillar system at a 900-ft depth and the least convergence at the 600-ft depth with the 88-ft-wide abutment pillar system. The convergence starts to increase about 100 ft outby the longwall face in the abutment zone and reaches a maximum well behind (inby) the face in the gob area.

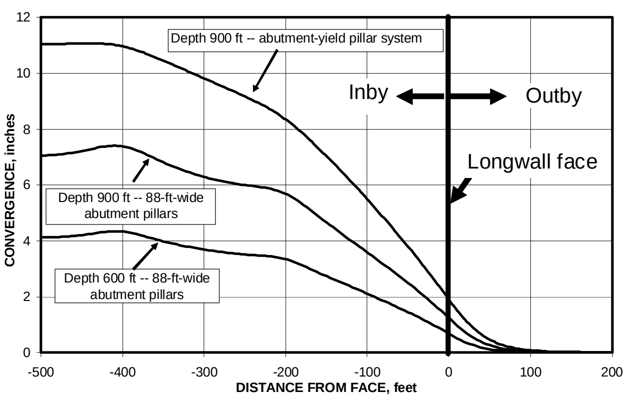

Figure 5. Roof-to-floor convergence calculated with LaModel. Negative numbers refer to locations inby the longwall face.

With the addition of standing support in each case shown in figure 5, the convergence was reduced by less than 1 pct, and the convergence curves if plotted would overlie the curve shown for no standing support without any noticeable difference at the scale of the figure. Thus, the roof-to-floor convergence curves for the standing support are not plotted on the figure. Table 1 shows the roof-to-floor convergence for the case of 900-ft depth with 88-ft-wide pillars and both 4- and 8-ft support spacing for selected positions from the face. The selected positions are in the abutment zone just outby the face, at the face, just behind the shields, and at the first crosscut inby the face. It is seen that there is very little difference in the convergence with or without standing support. Thus, it is concluded that the convergence produced by the main roof and floor activity and pillar yielding is uncontrollable or not influenced by the roof support system, regardless of the support.

Evaluation of Outby Abutment Loading with FLAC

The FLAC 2D finite difference software was used to investigate the interaction between rock failure and standing support in a tailgate entry subject to abutment loading. The model did not consider the effects of the longwall intersecting the entry nor the inby loading condition since these are three-dimensional conditions. The FLAC code is able to model large displacements and deformations that are associated with rock failure. It also has capabilities to realistically model roof bolts and standing supports.

Model Layout and Loading Conditions. The overall FLAC model geometry and boundary conditions are shown in figure 6. A typical three-entry gateroad design was evaluated in the study. The model was constructed to analyze the tailgate entry specifically, which is depicted in figure 6. Symmetry would satisfy loading conditions for the middle gateroad entry. The third entry has been eliminated by the first panel mining. The seam is approximately 6-ft thick and is overlain by a weak stack rock followed by interlayered black shale and thin coal rider beds. The mine roof is typically cut just below one of the rider beds to provide a stable horizon. The coal riders are overlain by weak black shales, grading to stronger gray shales. The shales are overlain by a 22-ft thick limestone bed. Figure 7 shows the model detail and geological profile in the vicinity of the entry.

The initial vertical stresses in the model were based on gravity loading only, while the horizontal stress were determined by the tectonic strains, which depends mainly on the elastic modulus of the rock, plus a Poisson effect component (Mark and Mucho, 1994; Dolinar, 2003). The input parameters were selected so that the horizontal stress in the moderately strong gray shale was 1,160 psi, similar to measured values in Eastern U.S. coal mines (Dolinar, 2003). The effect of an approaching longwall face was modeled by increasing the vertical stress by 1,044 psi, and the horizontal stress by 522 psi in three equal increments. The vertical stress increments were based on LaModel results. The model was found to be sensitive to the horizontal stress increments. The values finally used were selected to result in roof instability without standing support under abutment loading. This allowed the effect of standing support on rock failure development in the roof and associated closure of the tailgate entry to be evaluated.

The rock mass was modeled as a strain softening/ubiquitous joint material, using the built-in constitutive model in FLAC. This model is well suited to modeling the layered coal measure rocks, since the bedding layers can be described as strain softening ubiquitous joints, while failure of the rock matrix can be simulated as a strain softening Coulomb material. Great care was taken in setting up the models to replicate the geological sequence with as much detail as practical. Strength data for the different rock types included in the models were obtained from published data (Rusnak and Mark, 1999).

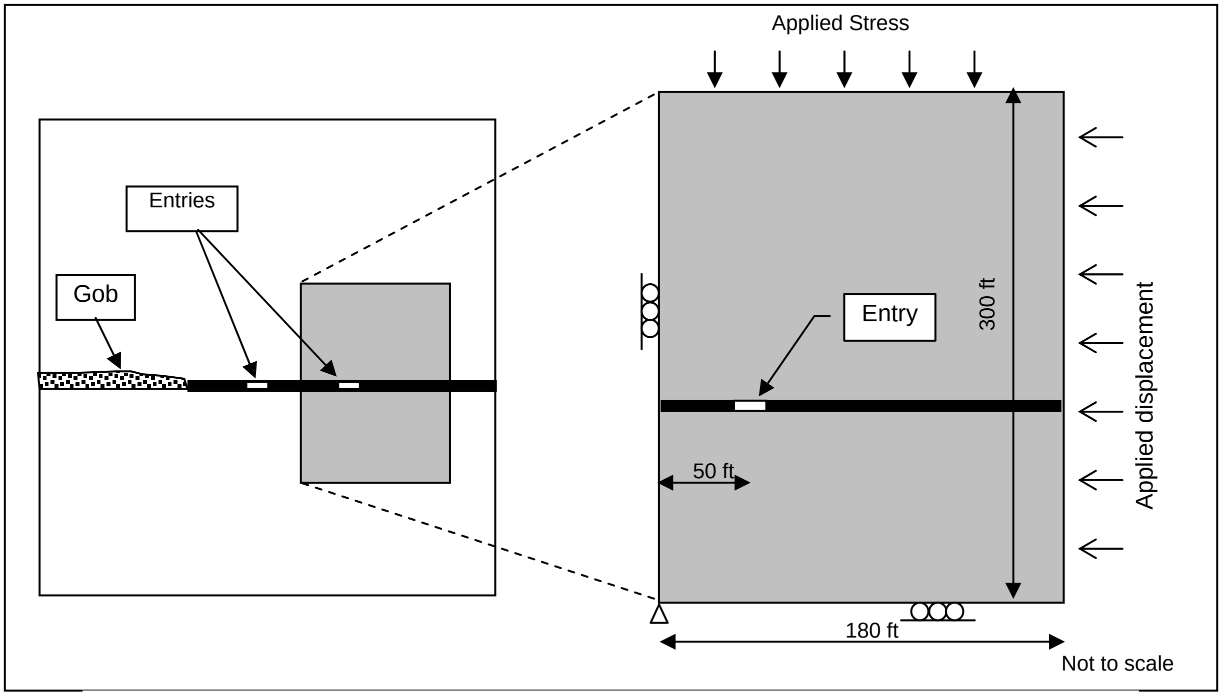

Figure 6. FLAC model geometry and boundary conditions.

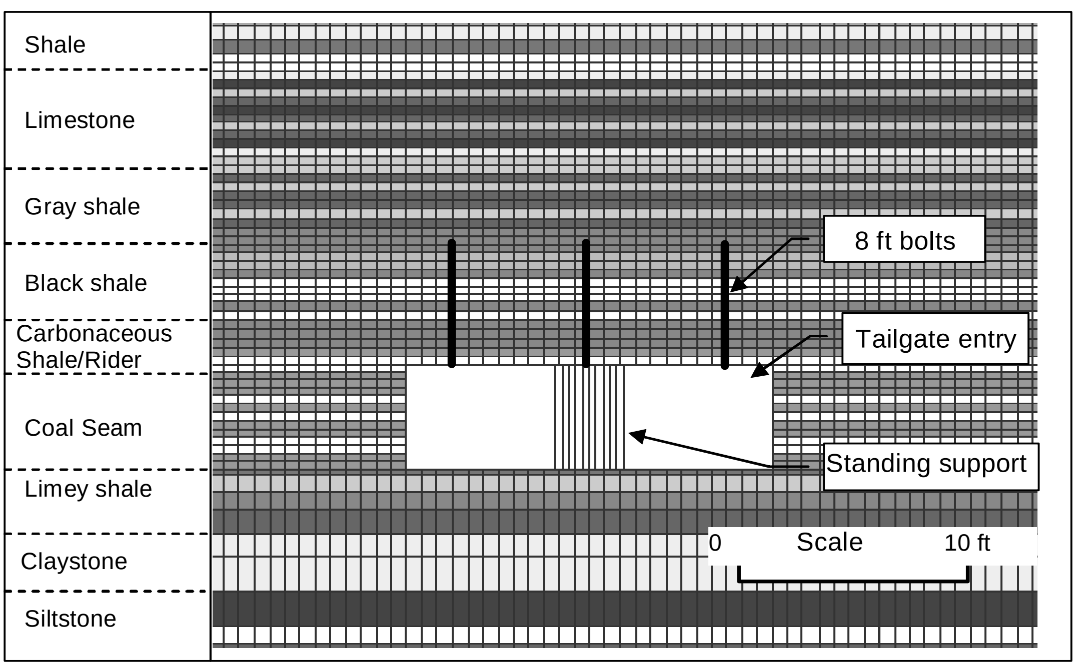

Figure 7. Detail of FLAC model showing element size and geological profile.

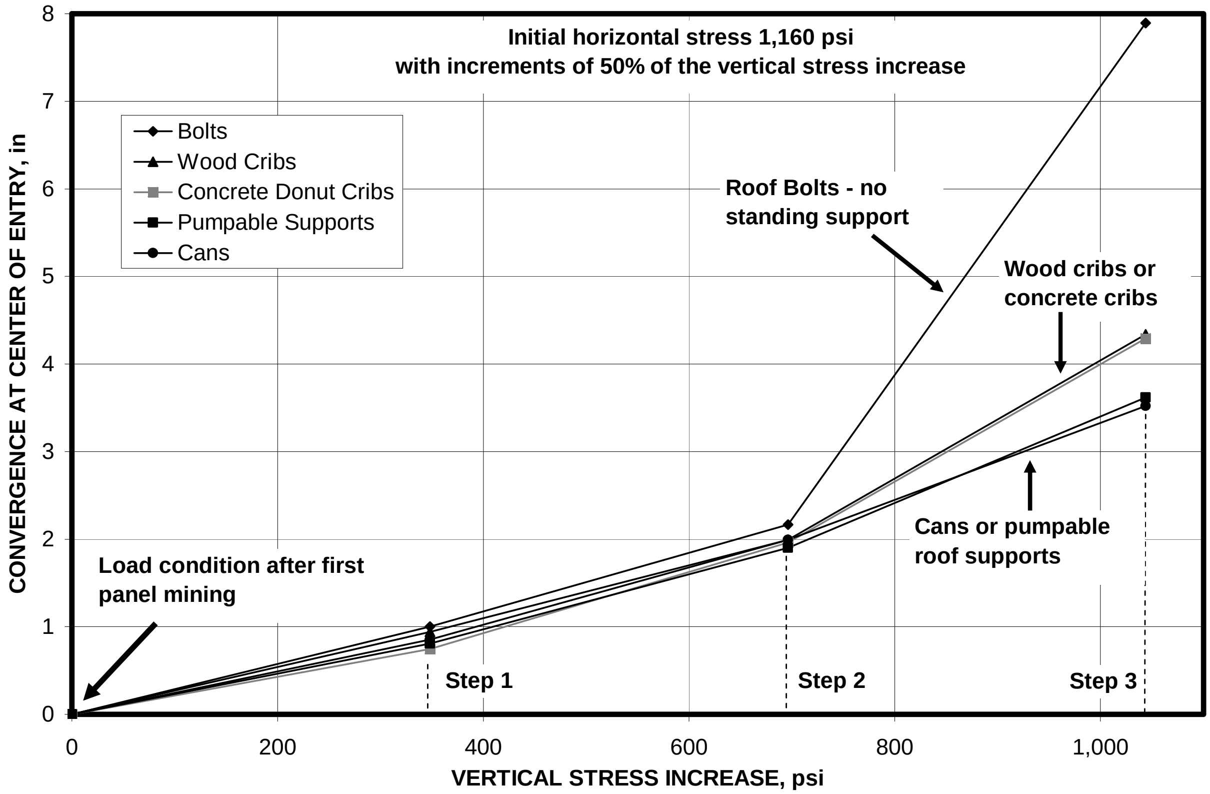

Figure 8. FLAC model results for three abutment loading steps showing tailgate closure versus vertical stress increase for roof bolts and various standing support systems.

The models included fully grouted roof bolts as well as the four standing support systems previously described. The grouted bolts were modeled using the pre-defined cable elements in FLAC. Bolts were 8 ft long with a yield capacity of 22 tons. An algorithm was developed using the internal programming language in FLAC to remove yielding sections of bolts to simulate bolt failure. In addition, roof collapse was modeled by removing elements in the roof that had experienced excessive plastic strain. Standing supports were modeled using the built-in support logic in FLAC, which allows the load-deformation characteristics shown in figure 3 to be accurately simulated. The standing support was installed after approximately 1 inch of tailgate closure resulting from the first panel mining.

FLAC Model Results for Abutment Loading. The FLAC model results for the different types of standing support are presented in the form of stress-closure curves in figure 8. Associated support loading for each of the three stress increment steps is shown in figure 9. Closure is reported at the center of the tailgate entry, while the stress is the abutment stress associated with the approaching longwall face, shown in three steps. The FLAC-calculated closures are generally larger than those determined by the LaModel program for abutment loading conditions. One reason for the difference is that FLAC simulates the rock failure and associated bulking in the immediate vicinity of the entry while LaModel does not account for this behavior.

Comparing the results of the model to measured field data in the Pittsburgh seam, the convergence determined from the FLAC models are higher than field measurements. A study of pumpable roof supports in a longwall tailgate at the Emerald Mine near Waynesburg, Pennsylvania measured convergence just outby the longwall face excluding the first foot of roof and floor rock movement ranging from 0.25 to 0.45 inches under a depth of cover of 750 ft (Barczak, et al., 2003). A previous study at the nearby Cumberland mine with wood cribbing and cable bolts measured convergence on the order of 1.75 inches in a longwall tailgate (Molinda, et al., 1997). The FLAC model shows 2-3 times this convergence at the maximum abutment stress considered in the analysis. This is a consequence of the selected horizontal stress increments used in the FLAC model.

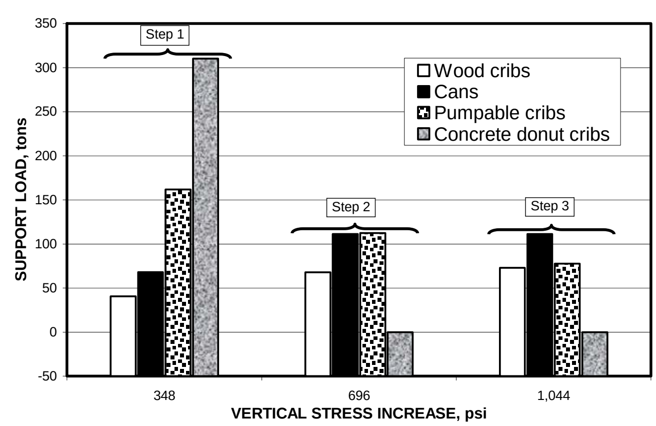

Figure 9. Support loads for each of the three vertical stress increments analyzed in the FLAC model.

The FLAC results show that the standing support has only a minor impact on the closure during the first two steps of abutment loading. It is only when the vertical stress is increased by 1,044 psi that one begins to see significant differences in convergence with and without the standing support. At this stress level, where the total vertical stress is 2.44 times the virgin stress, support consisting of bolts only is no longer capable of controlling the immediate roof as the closure approaches 8 inches. In comparison, the maximum convergence is less than 4.5 inches when any of the standing support systems are installed in the tailgate.

Among the four standing support systems analyzed in the study, the difference in closure was about 1 inch. The closure was approximately 4.4 inches when the tailgate was supported with wood cribs or concrete donut cribs and was 3.5 inches when the tailgate was supported with the Can supports or pumpable roof supports. The least convergence, 3.5 inches, occurred with the Can support, just slightly less than the 3.6 inches that occurred with the pumpable roof support system. The FLAC results indicate that in a situation where outby closure is less than 2 inches, the standing supports have little impact on roof behavior for the conditions analyzed in the model.

Examination of the deformation of the immediate roof (see figure 10) shows that for a tailgate entry with bolt support only, separation of strata occurs about 6 ft above the roof horizon. This separation indicates the onset of instability and inability of the support to control roof deflections. Smaller roof displacements are indicated for the concrete donut crib and the wood crib, while the Cans and pumpable roof supports maintain a tight roof without any separation. The results show that extensive yield capability, coupled with adequate support capacity, is required to maintain control over the roof deformation. The wood cribs, while having a large yield capacity, do not have sufficient resistance to prevent separation in the roof. The donut cribs, while having a significant initial capacity, do not have sufficient residual yield capacity to maintain control during extended closure.

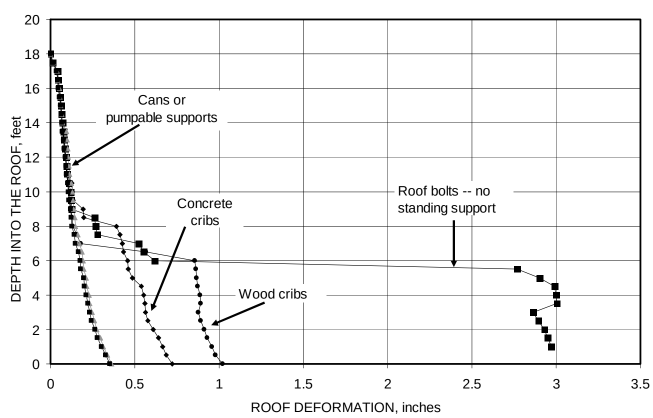

Figure 10. FLAC model results showing the displacement profile in the roof for various support systems after an increase in vertical stress of 1,044 psi (Loading Step 3 shown in figure 8).

STANDING SUPPORT DESIGN AND APPLICATION IMPLICATIONS

The results of these studies provide key insight into support design requirements. Some relevant issues for support design and application are discussed in more detail.

Surviving Uncontrollable Convergence

The first requirement for any standing support design is to recognize that in every application, there will be a component of the roof-to-floor closure that cannot be prevented by any standing support system. However, a standing support must survive this uncontrollable convergence without losing its support capability in order to be able to provide reinforcement and support of the immediate roof once the rock stress is relieved through further deformation. Hence, non-yielding support systems are not expected to perform well in longwall tailgate applications. Stiff support systems that shed load after reaching peak loading capacity may also have trouble in maintaining roof control if they are loaded beyond their peak loading outby the face and their residual load capacity is low.

How Much Uncontrollable Convergence Can Be Expected

A major portion of this uncontrollable convergence is caused by elastic deformations of the rock mass and yielding of the coal pillars. As such, the amount of uncontrollable convergence will increase with increasing depth of cover and decreasing pillar size. The LaModel study showed that the "uncontrollable" convergence at the longwall face was about 0.6 inches for a depth of cover of 600 ft and increased by a factor of two to 1.2 inches when the depth of cover was increased to 900 ft. The FLAC studies showed that additional uncontrolled convergence can be caused by the failure development of the near seam roof and floor rock mass. The uncontrollable convergence for the three levels of vertical stress considered in the analysis of outby loading conditions ranged from ¾ of inch to 4-1/2 inches. The amount of uncontrollable convergence will be site specific.

Benefit of Support Stiffness

Is there a benefit to using stiffer support systems? Stiffness is a measure of how quickly a support system develops its load-carrying capacity in relation to the roof-to-floor convergence. The stiffer the support, the more load capacity it will have for a given convergence. Since equilibrium of the roof and floor is a matter of force balance, then in general higher support stiffness will achieve equilibrium of the ground at less convergence, assuming the support has a positive stiffness (no load shedding) throughout the loading cycle. But how much is the benefit of the stiffer support? Is it a direct relationship? Does doubling of the support stiffness reduce the convergence by 50%?

The benefit of support stiffness depends on how the support interacts with the ground and the degree to which it can influence the development of failure within the immediate roof or floor. Figure 11 shows the convergence determined from the FLAC model for an increase in vertical stress of 348 psi (Step 1 of the analysis) as a function of the support load. The regression line suggests a nonlinear relationship between the support load and convergence. It is seen from this figure that higher support load results in less convergence. Figure 9 showed the loading of the four support systems for each of the stress increments analyzed in the FLAC model. The stiffest support (concrete donut cribs), had the least convergence; while the softest support (wood cribs) had the highest convergence at Step 1 (348 psi stress increment). However, the difference in convergence, less than ¼ of an inch, is small. A 662 pct increase in support load resulted in only a 24 pct reduction in convergence. The benefits of the stiffer supports are similar in the second stress increment of 696 psi shown as step 2, but become more pronounced when the stress is increased by 1,044 psi (Step 3). At the 1,044 psi stress increment, the soft wood cribs are allowing 0.86 more inches of convergence than the Can support (see Figure 9). In this case, a 53 pct increase in support capacity (Can compared to the wood crib), resulted in a 20 pct reduction in convergence.

Figure 11. Impact of support load on convergence after vertical stress increase of 348 psi in the FLAC model (Step 1 in figure 8).

In conclusion, the stiffness of the support will have a positive impact on controlling the ground and minimizing the convergence of the tailgate. The benefit is small until the near seam rock has strain softened and is depending on its residual load capacity for stability.

Impact of Support Load Shedding

One of the most revealing outcomes of this analysis was the impact that the concrete donut cribs had on the tailgate closure. The concrete donut crib acts as a non-yielding support reaching its ultimate capacity at less than 2 inches of convergence and then sheds its entire load at less than ¼ inch of additional convergence. It also has over 3.5 times the capacity of any other support and is the stiffest support considered in this analysis. However, it is somewhat surprising that at the highest loading condition (Step 3), equilibrium is attained at far less convergence than the tailgate supported only by bolts. One might expect the convergence to be closer to that of the tailgate supported with bolts only since the concrete donut crib is no longer providing any roof support. The roof behavior can be explained by reviewing the rock failure and roof bolt performance in the FLAC model. Figure 12 shows the development of shear bands in the surrounding rock at Step 3 for the tailgate supported only with roof bolts (figure 12b) and supported with concrete donut cribs in addition to the roof bolts (figure 12a). It is seen that the shear band development in the roof is substantially worse in the tailgate supported only by bolts, resulting in failure of the roof bolts. In the case of the tailgate supported by concrete donut cribs and bolts, the shear band development appears to have been inhibited by the high initial concrete donut crib resistance, preserving the roof bolts, which are still able to prevent large roof displacements at the Step 3 loading condition, after the concrete donut crib had failed.

A similar conclusion can be drawn from the pumpable roof support application. Examining figure 9, it is seen that the pumpable roof support had achieved more load than the Can support after Step 1. However, because the pumpable roof support sheds load after reaching its peak loading while the Can yields without shedding load, the pumpable roof support and the Can support have the same loading after Step 2 in the FLAC analysis. Comparing the convergence at Step 2 (see figure 8) shows that the tailgate supported with pumpable roof support had less convergence (1.90 inches) than the one supported with Can supports (2.00 inches). The early stiffness of the pumpable roof support compared to the Can support made a difference in the subsequent ground response. However, as the vertical stress continues to increase (Step 3) and more damage occurs to the immediate roof, the load shedding of the pumpable roof support will eventually cause more convergence to occur with this system than with the Can support that does not shed load (see figure 8).

CONCLUSIONS AND RECOMMENDATIONS

The development of innovative roof support systems continues with several new products being commercialized each year, each with a distinct load-displacement performance characteristic. The purpose of this study was to gain an understanding of the impact of the standing roof support system on ground control in longwall mining so that the most effective support can be utilized to minimize the risk of roof falls. Several conclusions have been made as a result of the numerical modeling studies of this problem. These conclusions are summarized as follows:

1. Standing supports <u>cannot</u> control or prevent convergence produced by main roof or floor activity or gateroad pillar yielding. Although this convergence most likely will not result in immediate instability of the roof, it is important from the perspective of the support design since it causes loading of the standing support.

2. Standing supports must be able to <u>survive "uncontrollable convergence"</u> associated with the elastic responses of the rock mass, particularly the main roof and floor activity, and the pillar response including its yielding behavior, in order to provide reinforcement and support of the immediate roof as the loading cycle continues.

3. Standing supports <u>do not</u> exhibit much control over the progressive failure development of the immediate roof, but can provide some degree of control over the post-failure (strain-softened) rock response.

4. The contribution of standing support in ground control is increased when the rock stresses increase, thus causing damage that cannot be fully controlled by the roof bolts.

5. The contribution of the standing support can directly impact the load development of the bolts, and at times, prevent or delay failure of the bolts. As such, the load path by which rock failure is developed can be altered by the standing support, resulting in more stable roof conditions than would be achieved without the application of standing supports.

6. Increasing the support stiffness can have a positive impact on ground control. The benefit may not be fully realized until the rock mass has failed and is behaving in accordance with its residual loading properties.

7. The Ground Reaction Curve is a concept that helps to explain the impact of roof and standing support on ground control. It should also be noted that the application of a particular standing support can alter the ground reaction curve. An assessment of the roof deformation and strata separations can provide additional insight into the capability of the support system to control the roof.

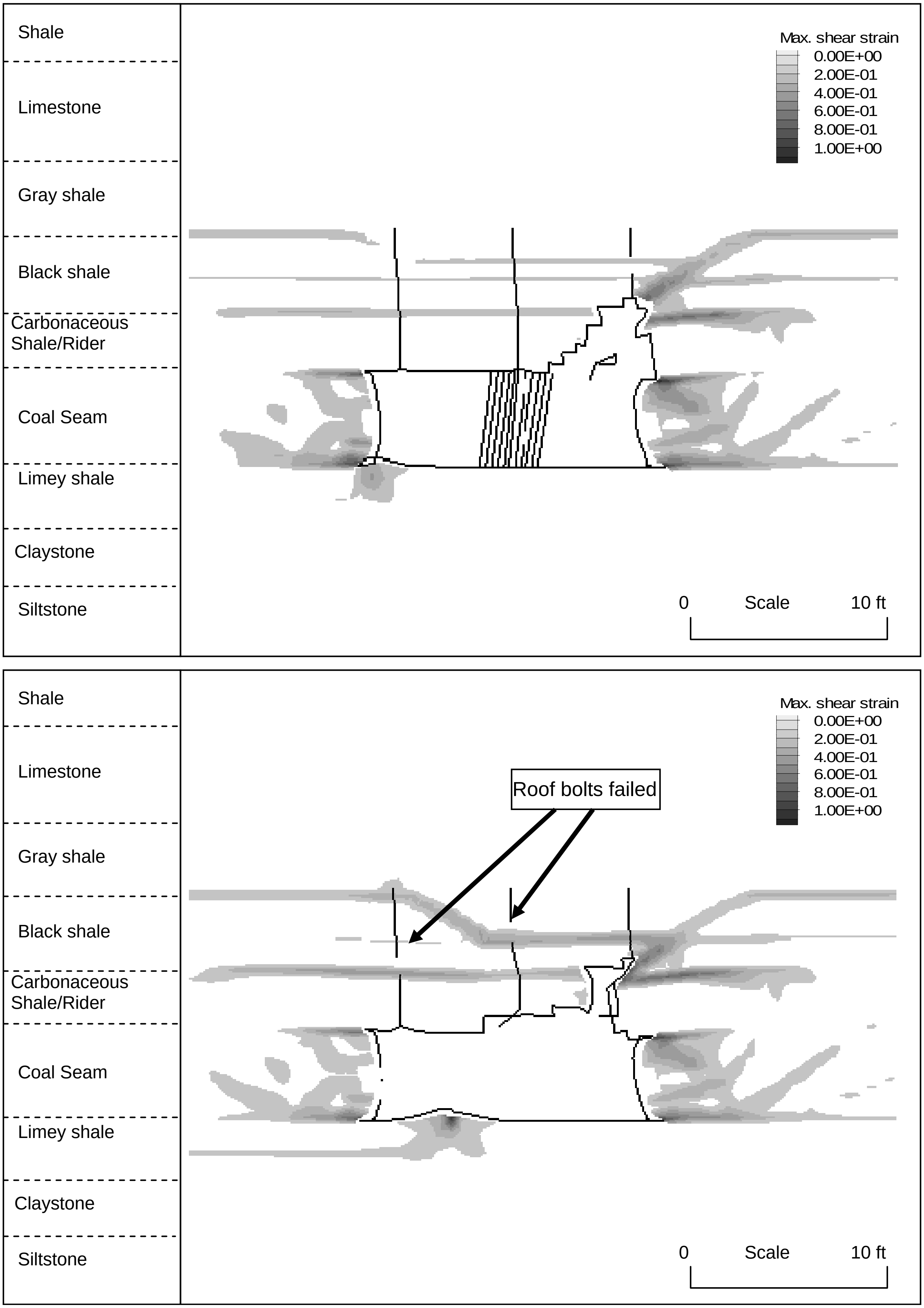

Figure 12. Comparison of roof conditions after loading step 3 with concrete donut cribs (a) and with entry supported only with bolts (b).

Finally, it is recommended that additional studies be conducted to further the understanding of support and strata interaction. First, additional roof geologies should be investigated with the 2-D FLAC modeling. This is critical since this study has shown that the support does have some impact on the failure development of the immediate roof. The roof structure analyzed in this study is a relatively weak, laminated structure. A more competent roof structure may respond quite differently. Next, a three-dimensional FLAC model needs to be developed to evaluate the face and inby loading conditions. Since there will be more failure within the immediate roof and floor for these conditions, standing support is expected to have more of an impact on ground control in these conditions. The LaModel results have already shown that the uncontrollable convergence inby the face can be quite large and will place additional demands on a standing support system operating in this environment.

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